

# Quality measurement of fruits and vegetables

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## Abstract

To investigate and control quality, one must be able to measure quality-related attributes. Quality of produce encompasses sensory attributes, nutritive values, chemical constituents, mechanical properties, functional properties and defects. Instrumental measurements are often preferred to sensory evaluations in research and commercial situations because they reduce variations in judgment among individuals and can provide a common language among researchers, industry and consumers. Essentially, electromagnetic (often optical) properties relate to appearance, mechanical properties to texture, and chemical properties to flavor (taste and aroma). Instruments can approximate human judgments by imitating the way people test the product or by measuring fundamental properties and combining those mathematically to categorize the quality. Only people can judge quality, but instruments that measure quality-related attributes are vital for research and for inspection. © 1999 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

The term quality implies the degree of excellence of a product or its suitability for a particular use. Quality is a human construct comprising many properties or characteristics. Quality of produce encompasses sensory properties (appearance, texture, taste and aroma), nutritive values, chemical constituents, mechanical properties, functional properties and defects.

Shewfelt (1999) points out that quality is often defined from either a product orientation or a consumer orientation. However, I personally have difficulty divorcing the two viewpoints and tend to think in terms of instrumental or sensory measurements of quality attributes that combine to provide an estimate of customer acceptability. Of course, one must always remember that there is more than one customer in the marketing chain. The next person or institution in the following

chain can be considered a customer by the previous one: grower, packer, distributor and/or wholesaler, retailer, produce manager, shelf stocker, shopper, and finally the ultimate consumer who actually eats the product. Each passes judgment, and each has its own set of quality or acceptability criteria, often biased by personal expectations and preferences. The component attributes of quality vary with context. The choice of what to measure, how to measure it, and what values are acceptable are determined by the person or institution requiring the measurement, with consideration of the intended use of the product and of the measurement, available technology, economics and often tradition. For grades and standards of a product, the definition of quality is formalized and institutionalized so it has the same meaning for everyone using it. Shewfelt (1999) suggests that the combination of characteristics of the product itself be termed quality and that the consumer's perception and response to those characteristics be referred to as acceptability. The dictionary definition of quality encompasses both concepts (*Webster's*; Neufeldt, 1988).

People use all of their senses to evaluate quality: sight, smell, taste, touch, and even hearing. The consumer integrates all of those sensory inputs—appearance, aroma, flavor, hand-feel, mouth-feel and chewing sounds—into a final judgment of the acceptability of that fruit or vegetable. Instrumental measurements are preferred over sensory evaluations for many research and commercial applications because instruments reduce variations among individuals, are more precise, and can provide a common language among researchers, industry and consumers. However, the relationship of the instrumental measurement to sensory attributes (e.g. descriptive analysis) and the relationship of those sensory attributes to consumer acceptability must be considered (see Shewfelt, 1999). Instruments may be designed to imitate human testing methods or may be statistically related to human perceptions and judgments to predict quality categories. Essentially, appearance is detected instrumentally by measuring electromagnetic (usually optical) properties, texture, by mechanical properties, and flavor (taste and aroma) by chemical properties.

Some sensors are based on signals not detectable by humans: for example, near infrared, X-ray, magnetic resonance and electrochemical.

Fruits and vegetables are notoriously variable, and the quality of individual pieces may differ greatly from the average. It is essential to determine statistically the number of pieces and the number of measurements per piece required to achieve significant, representative sampling. Sampling predicts the average quality, and perhaps quality distribution, of the lot. Sampling does not identify the undesirable or the outstanding individual fruit or vegetable. Sorting is necessary to segregate the undesirable, acceptable and outstanding individual pieces and to ensure the uniform quality required commercially. Sorting requires high-speed, non-destructive sensors to measure several attributes on each piece of fruit or vegetable, a means to combine those measurements into a classification decision, and a mechanism to physically place the piece into its proper category.

Often empirical methods developed to measure some particular quality attribute actually measure ripeness. Physiological processes involved in ripening and senescence occur together in a fairly predictable pattern. For example, measuring color might appear to be adequate to estimate firmness in peaches and tomatoes at harvest. However, growing conditions or postharvest treatments may decouple the physiological processes such that indirect measurements no longer predict quality as expected—e.g. the fruit softens but the color does not change. So it is essential to recognize what is really being measured and to respect the limitations of indirect measurement.

It is usually assumed that there is a consistent and unidirectional, although not always linear, relationship between the sensor response and the amount of the constituent or attribute. This is generally true of quantitative measurements, such as measuring pigment content by light absorbance or hardness by force to achieve a given deformation. However, this unidirectional relationship is not necessarily the case for acceptability. Consumers often prefer intermediate levels of a particular attribute to either very low or high levels; for instance, a firm tomato is preferred to one that is too hard or too soft. Some attributes are bino-

mial; for example, absence of decay is acceptable, presence is unacceptable. Research continues to establish the relationships among instrumental measurements, sensory intensity responses, and perceived quality or acceptability.

Methods to measure quality and quality-related attributes have been developed over centuries, with instrumentation appearing in about the past 80 years. Most recently, the emphasis has been on developing sensors for real-time, non-destructive sorting. There have been numerous reviews of technologies for non-destructive quality measurement, including those of Gunasekaran et al. (1985), Chen and Sun (1991), Tollner et al. (1993), Brown and Sarig (1994), Chen (1996), NRAES (1997), Dull et al. (1996) and Abbott et al. (1997). Some instrumental measurements—both destructive and non-destructive—that are extensively used in horticulture and several emerging technologies will be reviewed briefly. Due to space limits, only seminal or representative references are given.

## 2. Electromagnetic technologies

The electromagnetic spectrum encompasses, from longest to shortest wavelengths, radiowave, microwave, ultraviolet, visible light, infrared, X-ray and gamma-ray radiation. Optical properties indicate the response of matter to visible light wavelengths (400–700 nm, sometimes given as 380–770 nm), and usage is often extended to include ultraviolet (UV, 4–400 nm) and near infrared (NIR, 700 or 770 to 2500 nm). For convenience, the term light will be used loosely to encompass the UV, visible and NIR ranges in the following discussion unless otherwise qualified. However, now the UV is seldom used for horticultural quality measurement. X-ray is discussed separately. The other wavelength ranges have not been successfully applied to quality measurement of horticultural commodities.

### 2.1. Optical properties

Appearance is a primary factor in quality judgments of fruits and vegetables. Light reflected

from the product carries information used by inspectors and consumers to judge several aspects of quality; however, human vision is limited to a small region of the spectrum. Colorimeters measure light in terms of a tristimulus color space that relates to human vision; they are restricted to the visible light region. Some quality features respond to wavelengths in regions outside the visible spectrum. Spectrometers and spectrophotometers measure wavelengths in the UV, visible and NIR spectral regions; instruments are optimized for a particular wavelength range.

Optical properties are based on reflectance, transmittance, absorbance, or scatter of light by the product. When a fruit or vegetable is exposed to light, about 4% of the incident light is reflected at the outer surface, causing specular reflectance or gloss, and the remaining 96% of incident energy is transmitted through the surface into the cellular structure of the product where it is scattered by the small interfaces within the tissue or absorbed by cellular constituents (Birth, 1976) (Fig. 1). The complex physical structure of tissues creates an optically dense product that is difficult to penetrate and alters the pathlength traveled by the light so that the amount of tissue interrogated is not known with certainty. Most light energy penetrates only a very short distance and exits near the point of entry; this is the basis for color. But some penetrates deeper (usually a few millimeters, depending on optical density) into the tissues and is altered by differential absorbance of

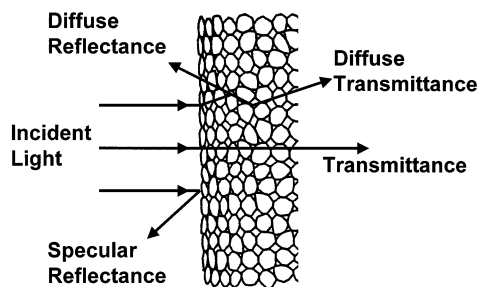


Fig. 1. Incident light on a fruit or vegetable results in specular reflectance (gloss), diffuse reflectance from features at depths to about 5 mm (body reflectance or interreflectance), diffuse transmittance, or absorbance. Color results from very shallow diffuse reflectance.

various wavelengths before exiting and therefore contains useful chemometric information (Fig. 1). Such light may be called diffuse reflectance, body reflectance, diffuse transmittance, body transmittance, or interactance; these terms are not always clearly distinguished.

Color is the basis for sorting many products into commercial grades, but concentration of pigments or other specific constituents might provide a better quality index (K.H. Norris, personal communication, 1967; Lancaster et al., 1997). Color relates more directly to consumer perception of appearance, pigment concentration may be more directly related to maturity, and concentration of certain other constituents relates more closely to flavor.

Color of an object can be described by several color coordinate systems (Clydesdale, 1978; Francis, 1980; Hunter and Harold, 1987; Minolta, 1994). Some of the most popular systems are RGB (red, green and blue), which is used in color video monitors, Hunter  $L^* a^* b^*$ , CIE (Commission Internationale de l'Eclairage)  $L^* a^* b^*$ , CIE XYZ, CIE  $L^* u^* v^*$ , CIE Yxy, and CIE LCH. These differ in the symmetry of the color space and in the coordinate system used to define points within that space. Of greatest importance to instrumental measurement are the tristimulus methods of the CIE and the similar Hunter system. According to CIE concepts, the human eye has three color receptors—red, green and blue—and all colors are combinations of those. The most commonly used notations are the CIE Yxy color space devised in 1931, the Hunter  $L^* a^* b^*$  developed in 1948 for photoelectric measurement, and the CIE  $L^* a^* b^*$  color space (Fig. 2) devised in 1976 to provide more uniform color differences in relation to human perception of differences. Color is measured by colorimeters in which the sensors are filtered to respond similarly to the human eye. Most provide automatic conversion among several color coordinate systems. Spectrophotometric data can be multiplied by three standard spectra representing the responses of the average human eye's three color receptors and then tristimulus values can be calculated. Automated color sorting is commercially used on packing lines for apples, peaches and several other horticultural commodities.

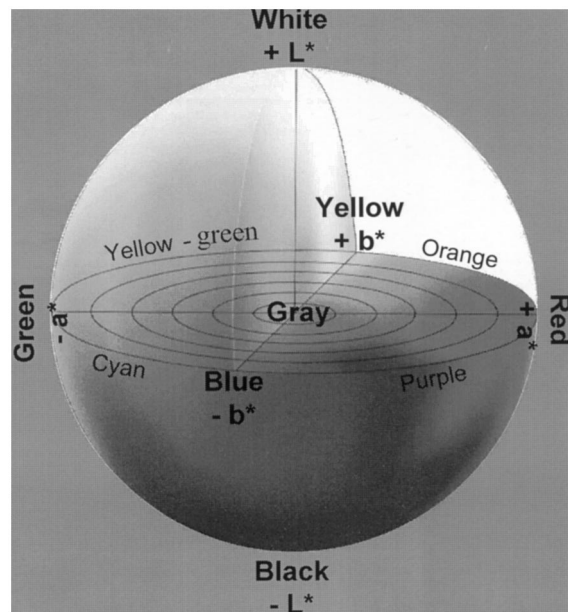


Fig. 2. CIE  $L^*a^*b^*$  color space.  $L^*$  indicates lightness, from white = 100 to black = 0;  $a^*$  and  $b^*$  are  $XY$  color coordinates indicating color directions;  $a^*$  is the red–green axis,  $b^*$  is the yellow and blue axis; the center is achromatic gray. Hue is location around the circumference and saturation is distance from center. Adapted from Minolta (1994) with permission.

Chemical bonds absorb light energy at specific wavelengths, so some compositional information can be determined from spectra measured by spectrophotometers or spectrometers. Within the visible wavelength range, the major absorbers are the pigments: chlorophylls, carotenoids, anthocyanins and other colored compounds. Water, carbohydrates, fats and proteins have absorption bands in the NIR region. Williams and Norris (1987) list some of the major absorption wavelengths for pigments, fats, proteins, carbohydrates and water. There is a vast literature on optical measurement of pigments and other constituents and on their relationships to maturity and quality. Currently multiwavelength or whole-spectra analytical methods are being developed for non-destructive determination of soluble solids, acids, starches and ripeness (Fig. 3). Starch or soluble solids (SS) content can be determined in intact fruit (apple, citrus, kiwifruit, mango, melons, onion, peach, potato and tomato) with  $R^2 \approx 0.93$

and SEC (standard error of calibration)  $\approx 0.5\%$  SS (Dull, 1984; Birth et al., 1985; Dull et al., 1989; Kawano et al., 1992, 1993; Murakami et al., 1994; Katayama et al., 1996; Slaughter et al., 1996; Lee et al., 1997; Pieris et al., 1998). Oil content is important in seeds, nuts, and avocados and can be determined using NIR (D.C. Slaughter, personal communication, 1996).

Multi- or hyperspectral cameras permit rapid acquisition of images at many wavelengths. Imaging at fewer than ten wavelengths is generally termed multispectral, and more than ten termed hyperspectral. The resulting dataset can be visualized as a cube with the  $X$  and  $Y$  dimensions being the length and width of the image (in pixels) and the  $Z$  dimension being spectral wavelengths; each datapoint is an intensity value. Alternatively, the dataset could be envisioned as a stack of single-wavelength pictures of the object, with as many pictures as the number of wavelengths used. Such imaging provides information about the spatial distribution of constituents (pigments, sugars, moisture, etc.) near the product's surface.

Differences between sound and damaged tissues in visible and NIR diffuse reflectance are useful for detecting bruises, chilling injury, scald, decay lesions and numerous other defects. Bruises on apples and peaches can be detected at specific NIR wavelengths; however, the wavelengths chosen for apple differ between fresh and aged bruises because of drying of the injured tissues

(Upchurch et al., 1994). Discriminant analysis of images of 18 common defects on several apple cultivars at 58 wavelengths between 460 and 1030 nm (Fig. 4) revealed that four wavelengths generally separated sound and damaged tissues: 540, 750, 970 and 1030 nm (Aneshansley et al., 1997; Throop and Aneshansley, 1997). Different wavelengths may be optimal for other commodities (Fig. 5). Differences in images taken at specific wavelengths—multispectral or hyperspectral imaging—and computerized image processing techniques are being used to automate detection and classification of many defects on-line. Such sorters are presently in the advanced commercial testing stage.

In addition to imaging technologies, the major advances in spectral analysis in recent years have been in statistical methods. Early analyses used multiple linear regression of raw, first difference, or second difference spectra (Hruschka, 1987). Later methods used various forms of data reduction such as principal component or partial least squares coupled with multiple regression. Present investigations focus on artificial neural networks (Chen et al., 1995; Song et al., 1995) and wavelets for data reduction. Each approach has advantages and disadvantages. Rapid scanning spectrophotometers are available and permit use of all or large parts of the spectrum. Optical-filter instruments or multispectral cameras require wavelength selection, rather than full-spectrum scanning. Limiting

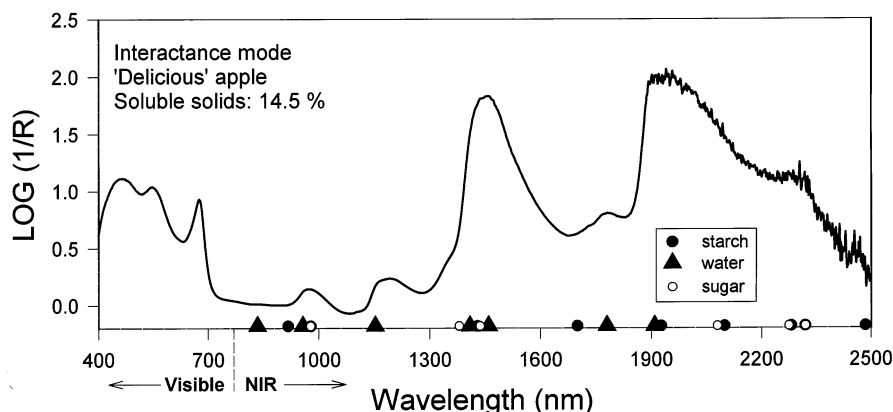


Fig. 3. Visible and near infrared interactance spectrum of 'Delicious' apple. Strongest absorption wavelengths of water, starch and sugar are indicated on the  $X$  axis.

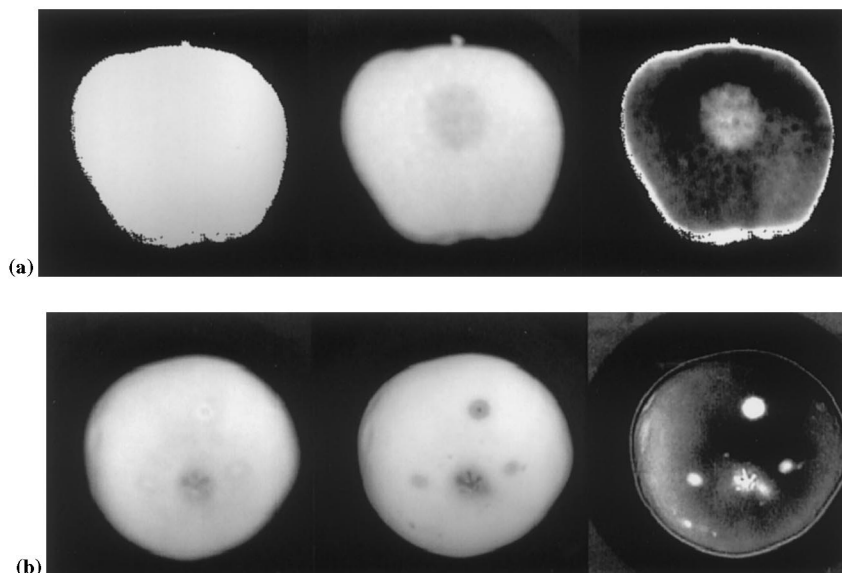


Fig. 4. Multispectral reflectance images of apple defects taken with a 35-nm bandwidth at each nominal wavelength. Top: bruise on 'Delicious' after 24 h (from left: standardized reference image at 540 nm, 1010 nm, binarized difference). Bottom: decay on 'Crispin' (from left: 1010 nm, 760 nm, binarized difference. (Aneshansley and Throop, unpublished.)

the number of wavelengths required reduces measurement time, even with acousto-optical or liquid crystal tunable filters, enabling application of optical measurement on-line for sorting operations at commercially acceptable speeds. Of course, limiting the number of wavelengths also reduces computational time; but it may also reduce the chemometric content of the data. Data processing of hyperspectral images is particularly complex, requiring the development of hybrid analyses using both spectroscopic and imaging concepts. New statistical methods are being developed to utilize hyperspectral images efficiently for quality assessment.

Regardless of the statistical methods, it is critical that the underlying relationship between the measurement and the quality attribute be valid and robust. There must be a fundamental relationship between the wavelength selection and the chemical(s) being sensed or the measurement will ultimately fail.

## 2.2. Fluorescence and delayed light emission

Fluorescence results from excitation of a molecule by high energy light (short wavelength) and its subsequent instantaneous relaxation with

the emission of lower energy light (longer wavelength). Many agricultural materials fluoresce; however, nearly all horticultural applications of fluorescence involve chlorophyll. In this review, fluorescence refers specifically to chlorophyll fluorescence unless otherwise stated. Delayed light emission (DLE) is a related phenomenon in which chlorophyll is excited by back reactions of photosynthetic intermediates and then relaxes as in fluorescence. Note that fluorescence and DLE are light emitted by excited chlorophyll, not merely reflected or transmitted light. Peak excitations of chlorophyll are induced by wavelengths around 420 nm (blue) or around 680 nm (red). The peak emission occurs at 690 nm with a small peak between 720 and 750 nm. Chlorophyll fluorescence in leaves has a lifetime of about 0.7 ns at 25°C (Butler and Norris, 1963); however, it can be detected during continuous illumination by properly filtered detectors and displays characteristic reaction kinetics (Fig. 6). DLE is detectable only in the dark following excitation. Because of photosynthetic kinetics, reproducible measurements of fluorescence or DLE are obtained only when excitation is preceded by a dark period, typically 10 min or longer.



Fig. 5. Multispectral reflectance images of tomato with viral ring spot (from left: 540 nm, 700 nm, binarized difference). (Abbott, unpublished.)

Fluorescence measurements of chlorophyll-containing tissue are routinely used for investigations of photosynthetic activity in plant leaves (Schreiber et al., 1975). Chlorophyll content and its photosynthetic capacity are often related to maturity of plant organs and to certain defects or injuries. Fluorescence and DLE have been studied as possible methods for evaluating maturity in fruits and vegetables that lose chlorophyll as they ripen or mature (Jacob et al., 1965; J.N. Yeatman, personal communication, 1967; Nakaji et al., 1978; Chuma and Nakaji, 1979; Chuma et al., 1980, 1982; Forbus et al., 1987, 1992; Abbott, 1996). Physiological stresses that affect chloroplasts or photosynthesis, such as temperature, salinity, moisture, atmospheric pollutants and mechanical damage can also affect fluorescence and DLE (Melcarek and Brown, 1977; Smillie and Nott, 1979; Abbott and Massie, 1985; Smillie et al., 1987; Chan and Forbus, 1988; Abbott et al., 1991, 1994, 1997; Toivonen, 1992; Lurie et al., 1994; DeEll et al., 1996; Tian et al., 1996; Woolf and Laing, 1996; Beaudry et al., 1997; Mir et al., 1998). It should be noted in this context that physiological stresses could affect maturity measurements using these principles and vice versa (Abbott et al., 1994, 1997).

A relatively new chlorophyll fluorescence technique is pulse amplitude modulated (PAM) fluorometry which measures features related to quenching due to electron transport, proton pumping of ATPase and pH gradients in the

thylakoid membrane. Studies using PAM fluorescence have been reported for following development of injury due to chilling (Lurie et al., 1994) and hot water treatments (Tian et al., 1996; Woolf and Laing, 1996). Woolf and Laing (1996) concluded that fluorescence reflects the effect of heat on the photosynthetic system in avocado fruit but does not necessarily indicate the overall condition of the skin.

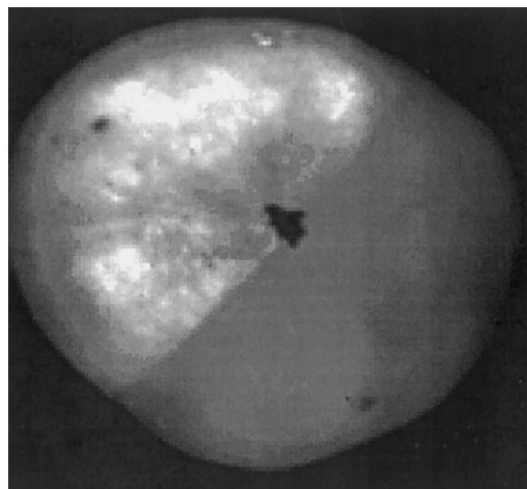


Fig. 6. Fluorescence image of mature green tomato with incipient chilling injury. Lower right half: steady-state fluorescence (10 min dark, then 3 min excitation). Upper left half: dark-adapted 13 min, immediate fluorescence upon excitation. Dark spots are insect injuries or blossom scar. Bright spots may indicate chilling stress (Abbott, Kim, McMurtrey and Chappell, unpublished).

Fluorescence or DLE imaging should enable visualization of the spatial distribution of stress responses before visible symptoms develop (Abbott, 1996). This should be of considerable interest in physiological studies of chilling injury and similar stress responses on fruits and vegetables.

A fluorescence application not based on chlorophyll was the detection of mechanical injury of citrus rind based on fluorescence of oils that leaked from damaged oil cells (Uozumi et al., 1987). Seiden et al. (1996) were able to distinguish two apple cultivars and to predict soluble solids content by the fluorescence of pasteurized apple juice excited at 265 and 315 nm and measured from 275 to 560 nm (not chlorophyll-related). Seiden et al. point out that sugars do not fluoresce but apparently develop in parallel with other compounds that do fluoresce.

### 2.3. X-ray

X-ray has been explored for inspecting the interior of agricultural commodities. The intensity of energy exiting the product is dependent upon the incident energy, absorption coefficient, density of the product and sample thickness. Due to the high moisture content in fruits and vegetables, water dominates X-ray absorption.

Anatomical and physiological changes within the tissue of fruits and vegetables—such as cell breakdown, water distribution and binding, decay and insect infestation—have negative effects on quality. Internal disorders cited in grade standards that should be detectable by X-ray include: cork spot, bitter pit, watercore and brown core for apple; blossom end decline, membranous stain, black rot, seed germination and freeze damage for citrus; and hollow heart, bruises and perhaps black heart for potato. Changes in the density of the internal tissue or distribution of water are usually associated with these defects, chilling injury and insect bodies or feeding.

Three X-ray techniques have been used for measuring the interior quality of fruits and vegetables. The most common is two-dimensional radiography, similar to that ordinarily used in medicine. Linescan radiography (Fig. 7), in which the product passes through a vertical plane of

X-ray energy, is most adaptable to on-line measurements. The other method is X-ray computed tomography (CT), also used in medicine. A CT scanner measures X-ray beams over several non-parallel paths through the object, computes a three-dimensional projection, and then computes a 'slice' of that projection. The intensity of the X-ray beam at the detector in all three methods is an integration (or summation) of the energy absorbed along the path from the emitter to detector. The pathlength through tissue increases from the edge toward the center of spherical or cylindrical products, so the apparent intensity is lowest at the center and must be compensated during image processing.

An early, successful application of X-ray was the detection of hollow heart in potato (Nylund and Lutz, 1950) (now commercially routine). Another commercially successful application took advantage of increasing density of lettuce heads during maturation (Lenker and Adrian, 1971; Schatzki et al., 1981). Researchers have investigated X-ray techniques for detecting watercore in apple, split pit in peach, the presence of pits in processed olive and cherry, freeze damage in citrus, bruises, and the presence or feeding of insects on numerous commodities (Tollner et al., 1992; Keagy et al., 1996; Schatzki et al., 1997). Brecht et al. (1991) used CT to determine maturity of green tomatoes. With limited success, internal sprouting and ring separations due to microbial rot in onion were detected with X-ray linescan (Fig. 7) (Tollner et al. 1995).

### 2.4. Magnetic resonance and magnetic resonance imaging (MRI)

Certain nuclei, including  $^1\text{H}$ ,  $^{13}\text{C}$ ,  $^{31}\text{P}$  and  $^{23}\text{Na}$ , have a magnetic moment and align along a strong static magnetic field (Faust et al., 1997). The  $^1\text{H}$  magnetic resonance is of greatest horticultural interest. A weak pulse of the proper radiofrequency (RF, based on magnetic field strength) will cause the net magnetic moment to rotate  $90^\circ$ . When the RF signal is removed, the moment loses energy and relaxes back to its previous position. Energy released by relaxation induces an RF signal in a receiver coil. Energy loss is differential



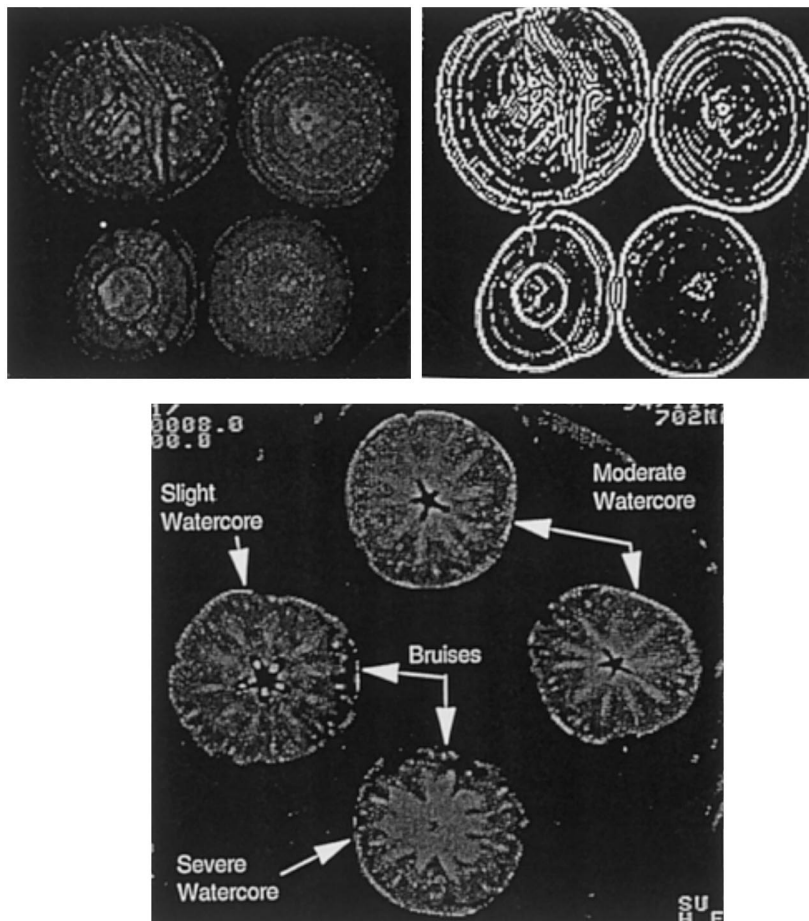


Fig. 7. X-ray images. Top: linescan image for detecting ring separations in onions (from left: original image, Sobel filter processed image); from Tollner et al. (1995). Bottom: computed X-ray tomography image of apples showing bruises and watercore; from Tollner et al. (1992).

and is based on the environment surrounding each nucleus.  $T_1$  (spin–lattice) relaxation times represent energy loss to the surrounding environment (called the lattice), whereas  $T_2$  relaxation times (spin–spin) represent loss due to interaction of the spins of multiple nuclei with respect to each other. Images (MRI) are created by applying a magnetic gradient in one direction (phase encoding) and an RF gradient in the other direction (frequency encoding); gradients permit the reconstruction of spatial information.  $T_2$  values are often used to describe the biological state of tissues (Faust et al., 1997) and are generally interpreted as the ratio of bound water to free water.

Of particular interest in horticultural applications, areas of greater free water content are brighter than surrounding tissues in MRI, so that disorders involving water distribution—watercore, core breakdown, chilling injury, bruising, decay, presence or feeding of insects, etc.—can be visualized. Applications of MR and MRI in horticulture have recently been reviewed by Clark et al. (1997), Faust et al. (1997) and Abbott et al. (1997).

Hinshaw et al. (1979) published MRI of ‘Satsuma’ orange showing the membranes (0.5 mm thick) separating segments. Wang et al. (1988) demonstrated the presence of watercore in an

apple, as well as showing internal structure. MRI has been used to show morphology, ripening, core breakdown, seeds or pits, voids, pathogen invasion, worm damage, bruises, dry regions, and changes due to ripening, heat, chilling and freezing (Chen et al., 1989; Saltveit, 1991; MacFall and Johnson, 1994; Akimoto et al., 1995; Clark et al.,

1997; Faust et al., 1997). Fig. 8 shows MRI of apples, displaying internal structure and bruising.

Another approach to utilizing  $^1\text{H}$  MR involves interrogating a region within the fruit or vegetable, rather than imaging. Although this method does not provide spatial information and thus limits the information that can be obtained, it

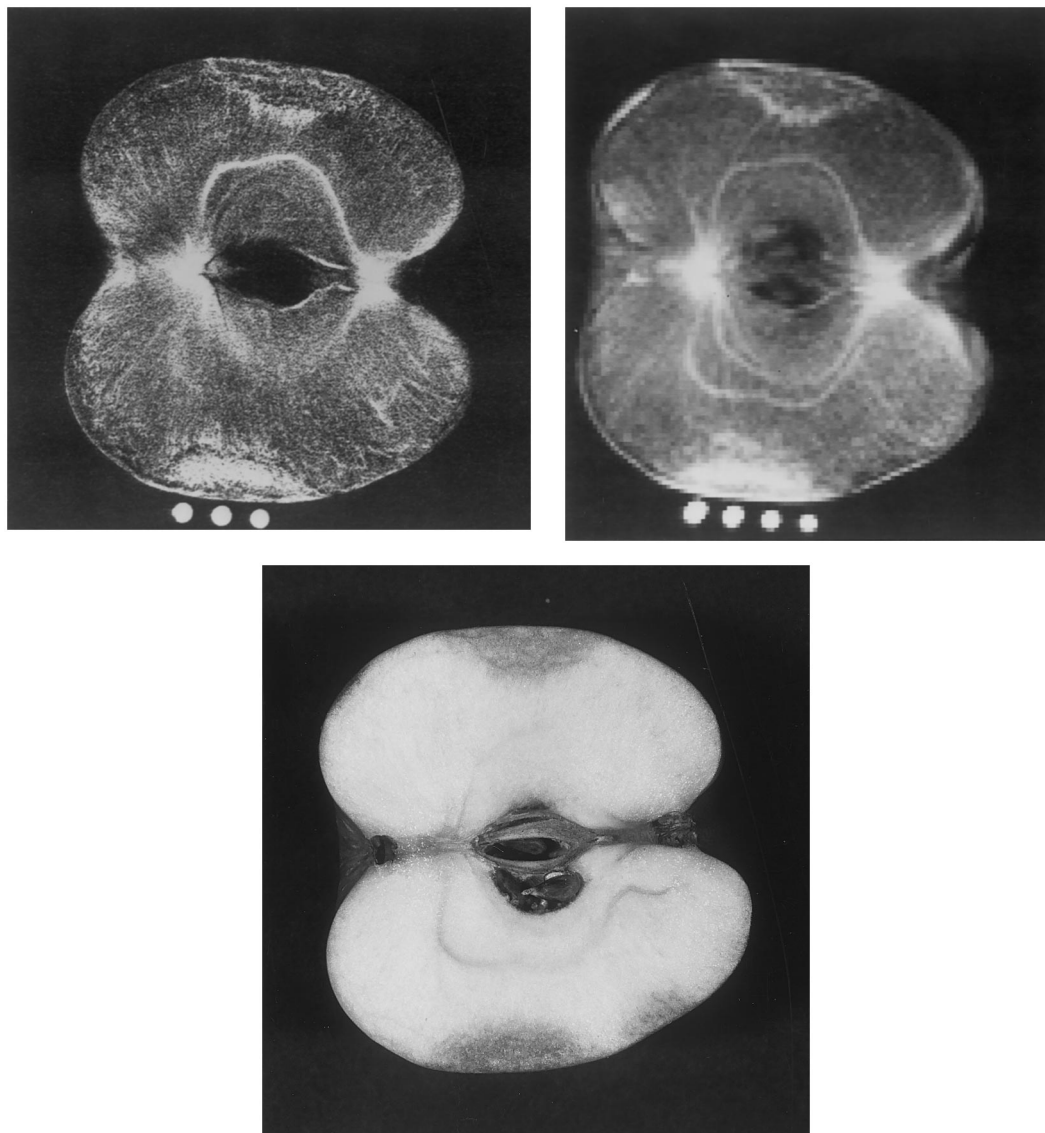


Fig. 8. Magnetic resonance images of intact 'Delicious' apple with three bruises: 1-h-old bruise at bottom, 48-h bruise at top, and small old bruise at upper left. From left:  $512 \times 512$  pixel resolution, 40 ms echo delay (TE) and 2-mm computed slice;  $128 \times 128$  pixel resolution, 40 ms TE and 2-mm slice; visible light photograph of the same apple cut through the scanning plane. From Chen et al. (1989).

dramatically reduces the complexity and cost of instrumentation. Akimoto (1984) patented an MR method for grading fruit based on sugars and/or organic acids. MR has been used to detect pits in halved red sour cherries and correlated to firmness, dry matter, soluble solids content, total acidity and Brix acid ratios in several fruits (Chen et al., 1996; Cho et al., 1993; Stroshine et al., 1994).

Currently, MR and MRI are not practical for routine quality testing. MR equipment is expensive and difficult to operate; but, like all technologies, it is becoming cheaper, faster and more feasible for research and specialized applications. MR techniques have great potential for evaluating the internal quality of fruits and vegetables.

### 3. Mechanical technologies

Mechanical properties relate to texture. Harker et al. (1997) recently reviewed the cellular basis of fruit texture and the human physiology involved in its perception. Mechanical tests of texture include the familiar puncture, compression and shear tests, as well as creep, impact, sonic and ultrasonic methods, recently reviewed by Brown and Sarig (1994), Chen (1996) and Abbott et al. (1997). Under mechanical loading, fruits and vegetables exhibit viscoelastic behavior which depends on both the amount of force applied and the rate of loading. However, for practical purposes, they are often assumed to be elastic and loading rate is largely ignored. Measurement of elastic properties requires consideration of only force and deformation, whereas viscoelastic measurement involves functions of force, deformation and time. Nonetheless, because even the firmest fruits and vegetables do have a viscous component to their force/deformation (F/D) behavior, loading rate (test speed) should be held constant in instrumental tests and should be reported.

The viscous component has minimal contribution to perceived texture in most firm fruits and vegetables (e.g. apple or carrot), but is quite significant in soft fruits, notably tomato, cherry and citrus, particularly contributing to hand-feel. That is why a creep or relaxation measurement is often

more suitable for the latter products than is a puncture test. The viscous component of texture is important in determining bruise resistance, even in firm products like potato (Bajema et al., 1998). Although bruise resistance (as distinguished from the presence of bruises) is not considered in evaluating the quality of individual specimens, it should be considered in evaluating the quality of breeding lines in commodities where bruising causes commercial loss. The viscous component is also important in developing handling equipment.

Most non-destructive mechanical methods measure elastic properties (e.g. modulus of elasticity—Young's modulus) at very small deformations. Modulus of elasticity measures the capacity of the material to take elastic deformation and is the stress-strain ratio, commonly measured by the slope of the F/D curve prior to rupture for a tissue specimen with constant cross-sectional area (Fig. 9). (Stress is force per unit area; strain is deformation as proportion of initial length.)

It should be noted that fundamental tests and material properties measurements like the elastic modulus were developed by materials engineers to study the strength of materials for construction or manufacture. Once the failure point of such a material is exceeded, the material is of little interest. Thus materials engineers would not be interested in the portion of the F/D curve beyond the bioyield point, certainly not beyond the rupture point. The food scientist, on the other hand, is interested in the breakdown of the food in the mouth until it is swallowed. Does peach flesh melt or is it stringy? Does apple flesh break crisply or is it mealy? Is a baked potato waxy or mealy? As Bourne (1982) pointed out, "food texture measurement might be considered more as a study of the weakness of materials rather than strength of materials." In fact, both strength and breakdown characteristics are important components in the texture of fruits and vegetables.

#### 3.1. *Quasi static force/deformation tests*

Puncture or compression tests made at relatively low speeds, typical of such instruments as the Magness-Taylor fruit firmness tester and electronic universal (F/D) testing instruments, are

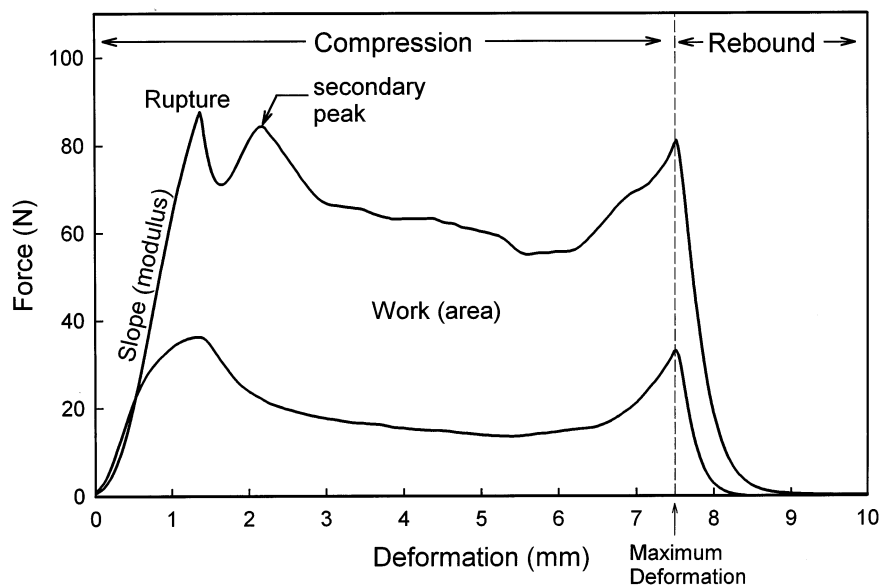


Fig. 9. Force/deformation (F/D) curves for cylindrical tissue specimens (10 mm high  $\times$  15 mm diameter) from firm and soft apples under constant strain-rate ( $0.42 \text{ mm s}^{-1}$ ) compression. F/D curves for puncture are similar except that they are usually terminated at the maximum deformation.

considered quasi static. Typical F/D curves for cylindrical apple specimens under constant strain-rate compression are shown in Fig. 9. The portion of the initial slope up to inflection represents non-destructive elastic deformation. Beyond that portion, cells start to rupture and there may be a bioyield point where a noticeable change in slope occurs before the rupture point at which significant tissue failure occurs. In some F/D curves, including those in Fig. 9, bioyield may not be distinguishable from rupture (Bourne, 1965). Beyond rupture, the force may again increase, level off, or decrease as deformation increases. At the maximum deformation point, the probe is withdrawn and the force diminishes until contact is lost. Puncture F/D curves appear similar to compression curves.

Firmness of horticultural products can be measured by compression or puncture with various probes at different force or deformation levels, depending on the purpose of the measurement and how the quality attributes are defined. Horticulturists tend to define firmness as the maximum force attained, although sometimes the rupture or bioyield force is used. The maximum force, re-

gardless of where it occurs, is defined as firmness in the popular Magness–Taylor penetrometer test and usually also in the Kramer multiblade shear test (widely used by the food processing industry to test fruits and vegetables). On the other hand, the slope of the F/D curve, reflecting elastic modulus, is often used by materials engineers as an index of firmness. Because sample dimensions, and thus stress and strain, are seldom known precisely in most food tests, this slope measurement should be termed apparent elastic modulus (but seldom is). Elastic modulus can be measured non-destructively, whereas bioyield and rupture by definition require some cellular damage. The best relationships to sensory firmness, hardness and crispness are obtained with forces at or beyond deformations that cause tissue damage (Mohsenin, 1977; Bourne, 1982). Therefore a non-destructive measurement is unlikely to produce excellent prediction of these textural attributes or of Magness–Taylor (or similar) test values, although useful levels of prediction may be attained in tissues where elastic modulus and rupture strength are closely correlated. Quasi static tests do not predict impact properties (G.M. Hyde, 1998, personal communication).

Penetrometer testers such as the Magness–Taylor (MT) Fruit Firmness Tester (often improperly called a pressure tester), the Effe-gi, McCormick and Lake City Electronic Pressure Tester (all derived from the MT), and the similar U.C. Firmness Tester, are widely used for firm-to-hard fruits and vegetables. The MT tester was developed primarily as an objective measurement of picking maturity (Magness and Taylor, 1925), not as a postharvest quality measurement. Haller (1941) reviewed the use of the MT and its suitability for maturity and storage tests of a number of commodities. A research committee proposed a standardized method for making MT measurements (Blanpied et al., 1978) that also should be applied to related testers. Penetrometer measurements are moderately well correlated with human perception of firmness and with storage life, and consequently this technique has received widespread acceptance for a number of horticultural commodities, such as apple, cucumber, kiwifruit, pear and peach. However, several studies have shown that caution is warranted in the use of such tests for determining quality. Bourne (1979) stated that, while MT is almost the only method used by horticulturists to measure texture, there needs to be a wider understanding of the multi-dimensional nature of texture and the fact that firmness is only one of the group of properties that constitute texture. Two decades later, the need for this understanding persists.

Soft juicy fruits such as tomato, cherry, citrus and various berry fruits often have a significant viscous component to their texture. Instruments that measure creep (deformation under a constant load for a specific time) are popular for measuring firmness of soft horticultural commodities. There is currently no commonly accepted commercial instrument for this measurement. Although the Cornell firmness tester (Hamson, 1952) is sometimes used to measure tomato firmness, the loads and times applied are not standardized. Another related measurement that is sometimes used is relaxation (decrease in force with time at a constant deformation). There also is no commonly accepted standard method for this measurement.

Plunger tip geometry (i.e. size and shape) must be carefully considered in any mechanical test. For example, Jackman et al. (1990) found that a flat-plate probe could not detect firmness differences between sound tomatoes and those with slight chilling injury, whereas a rounded punch probe did. The common geometries for probes include spherical, rounded or flat-surfaced cylinders (diameter much smaller than that of the specimen), cones and flat plates (diameter greater than diameter of contact with the specimen). The instrument, probe geometry, deformation or penetration distance and rate of loading (speed) used in texture tests should always be reported. A recent problem with firmness tests is the use of probes of varied geometries under the generic term Magness–Taylor. The authentic MT probes—there are two—have gently

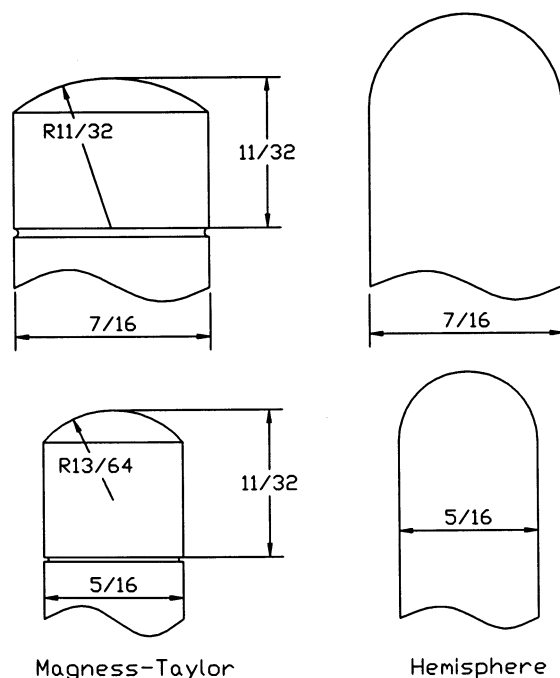


Fig. 10. Geometry and dimensions of popular puncture probes. Left: authentic Magness–Taylor (MT) probes (dimensions shown in inches for precision because original MT specifications are in inches;  $7/16$  inch  $\approx 11.1$  mm,  $5/16$  inch  $\approx 7.9$  mm). Right: probes with the same diameter but hemispherical tip. Simple cylindrical probes and other geometries are also used for puncture tests.

rounded tips (of specified radii of curvature), not hemispherical or flat tips (Fig. 10) (J.F. Cook, Jr., Past President, D. Ballauff Mfr. Co., Laurel, MD, personal communication, 1998). Because of the curvature of the MT probes and the fact that firmness as measured in puncture is a combination of shear and compression, it is not possible to convert measurements made with one MT probe to the other MT size, or to convert to or from values for probes of other geometries (Bourne, 1982).

Due to their low speeds and often destructive nature, compression and penetration F/D techniques are not very adaptable for on-line sorting of horticultural products. Numerous methods for rapid, non-destructive texture measurement have been developed based on responses to very small deformations, vibrations, air puffs (Prussia et al., 1994) and impacts. These were recently reviewed by Abbott et al. (1997). None has gained widespread acceptance, nor has any been shown to predict MT firmness reliably, although correlations as high as 0.94 have been obtained in some tests (Abbott and Massie, 1998).

### 3.2. Impact

There are various forms of impact test in which the force/time or force/frequency spectrum is recorded as the fruit is dropped onto a force transducer or as the transducer impacts the fruit. A number of impact parameters have been related to firmness: peak force, ratio of peak force to time-to-peak (or time squared), coefficient of restitution, contact time and frequency spectrum. Bajema et al. (1998) developed an impact tester for research on bruise resistance. Delwiche et al. (1989) developed a single-lane firmness sorting system with a rate of 5 fruit  $s^{-1}$  for sorting pear and peach. Delwiche and Sarig (1991) and Sugiyama et al. (1994) developed probe impact sensors that use peak force or coefficient of restitution for firmness measurement. McGlone and Schaare (1993) and Patel et al. (1993) reported on impact firmness instruments for research, quality control and sorting. Zapp et al. (1990) developed an instrumented sphere, simulating a fruit, to determine the impact history during handling, packing and transport of fruits and vegetables.

### 3.3. Sonic and ultrasonic vibration

Sonic (or acoustic) vibrations encompass the audible frequencies between about 20 Hz and  $\approx 15$  kHz; ultrasonic vibrations are above the audible frequency range ( $> 20$  kHz). Sonic and ultrasonic waves can be transmitted, reflected, refracted or diffracted as they interact with the material. Wave propagation velocity, attenuation and reflection are the important parameters used to evaluate the tissue properties of horticultural commodities.

When an object is excited at sonic frequencies, it vibrates. At particular frequencies it will vibrate more vigorously, causing amplitude peaks; such a condition is referred to as resonance. Resonant frequencies are related to elasticity, internal friction or damping, shape, size and density. The firmer the flesh, the higher the resonant frequency for products of the same size and shape. The traditional watermelon ripeness test is based on the acoustic principle, where one thumps the melon and listens to the pitch (frequency) of the resonance. The sonic vibration method is truly non-destructive and is suitable for rapid firmness measurement. Sonic measurement generally represents the mechanical properties of the entire fruit, unlike puncture or compression which samples localized tissues.

Stiffness coefficients incorporating resonant frequency and mass can compensate for size differences; however, shape also influences sonic firmness measurements (Lu and Abbott, 1997). Sonic measurement is an excellent means for following changes in individuals over time in research applications and is suitable for determining average firmness of lots of fruit, but has not always proved capable of predicting the MT firmness of individual fruit (Abbott et al., 1968, 1995; Saltveit et al., 1985; Armstrong et al., 1990; Peleg et al., 1990; Stone et al., 1994; Shmulevich et al., 1995). In apples, correlation coefficients between sonic stiffness coefficients and MT values have ranged from 0.5 to 0.9, depending on cultivar, storage conditions, MT range, sample size and method of excitation. Correlations of  $> 0.9$  have been obtained for kiwifruit (Abbott and Massie, 1998). Abbott et al. (1997) reviewed various appli-

cations, methods and theoretical studies of this method.

Ultrasonic waves can be transmitted, reflected, refracted or diffracted as they interact with the material. Wave propagation velocity, attenuation and reflection are the important ultrasonic parameters used to evaluate the tissue properties of horticultural commodities. However, because of the structure and air spaces in fruits and vegetables, it is difficult to transmit sufficient ultrasonic energy through them to obtain useful measurements. Upchurch et al. (1987) attempted to detect bruises in apple, and Galili et al. (1993) found that ultrasonic measurements could be used for firmness determination in some fruits but that a more powerful ultrasonic source is required to penetrate others. Despite numerous studies, few applications have developed (Abbott et al., 1997).

#### 4. Electrochemical technologies

The concentration of volatiles within a fruit or vegetable increases as it ripens and their release to the surrounding atmosphere is responsible for the product's pleasing aroma. Aromatic and non-aromatic volatiles are released, including ethylene, ethyl esters, acetaldehyde, ethanol and acetate esters. The electrical conductivity of semiconductor gas detectors, based on different polymers and metal oxides, decreases on exposure to volatiles. Although the detectors are not specific for particular volatiles, each type is generally sensitive to a particular class of compounds. A battery of several detectors can produce a 'fingerprint' that may indicate maturity or presence of some disorders. The electronic sniffer concept (Benady et al., 1995; Simon et al., 1996) has been tested on apples, blueberries, melons and strawberries. Further research is needed to explore the selection of semiconductors and to relate the fingerprints to quality categories.

#### 5. Statistical methods

Significant advances have been made in the practical application of classical statistical meth-

ods and in the development of new methods for relating instrumental data to quality assessments, quality categories and acceptability judgments. Statistical methods are used for data reduction—the selection of measurement variables, such as wavelength, for predicting quality—and for product classification. Some of the newer methods in this context are partial least squares, principal components, factor analyses, artificial neural networks and wavelet analysis. Applications of numerical modeling are aiding in the understanding of sensor responses, such as finite element modeling of vibrational behavior or modeling progressive changes in chemical composition. Advances in machine vision and image processing require statistical pattern recognition, involving histogram analysis, edge recognition, dynamic thresholding and visual texture analysis. There is growing recognition that quality is a multifaceted attribute and there is increasing interest in "sensor fusion" or combining several inputs—different measurements from a single sensor, measurements on different parts of a product (views), or measurements from different sensors—into a quality classification decision (Chen et al., 1995; Heineemann et al., 1995; Ozer et al., 1995). In addition to classical discriminant, cluster and principal component analyses, researchers are investigating newer computer-intensive multivariate statistical methods such as recursive classification trees and artificial neural networks.

However, it is essential to use judgment in the application of these statistical methods. In the absence of fundamental relationships between the measurement and the quality attribute—for example, light energy absorbance by chemical bonds in spectrophotometric measurement—spurious relationships may be found under particular circumstances. When the circumstances change, the relationship is no longer there and the new measurement no longer predicts the quality attribute. Much time and money can be invested in a meaningless measurement if care is not taken to ensure that it is fundamentally valid and robust. One cannot substitute statistical analyses for the knowledge and judgment of the investigator.

## 6. Overview and conclusions

Quality is not a single, well-defined attribute but comprises many properties or characteristics. Statistical combination of measurements by several sensors will increase the likelihood of predicting overall quality. However, sensor testing and calibration must include a wide range of conditions. It is important that what is really being detected is understood so the limitations are appreciated. Of course, there are different requirements for laboratory and industry applications.

Appearance is one of the major factors the consumer uses to evaluate the quality of fruits and vegetables, and measurement of optical properties has been one of the most successful instrument techniques for assessing quality. Many products are routinely sorted for color. Optical methods are being developed for on-line detection of surface defects based on optical measurements in the visible or NIR regions. Optical systems, especially in the NIR region, and newer software make it possible to detect carbohydrates, proteins and fats that may improve quality indexes. It is likely that on-line NIR sensing of soluble solids will be routine in the near future. Multispectral and hyperspectral imaging provide spectral information at multiple wavelengths in addition to spatial information. Differential reflectance of various wavelengths from sound and defective tissue enable detection and often identification of the defects. Fluorescence can detect surface damage on products with significant amounts of chlorophyll; laboratory instruments are readily available. Electronic sniffers based on the responses of semiconducting materials to volatiles may be able to accurately classify a number of fruits into ripeness or aroma quality categories. X-ray inspection systems are now used to detect internal defects on-line in some limited applications, but the increasing sensitivity of the equipment and the development of rapid image processing could soon make this technology more available. MRI has great potential for evaluating the quality of fruits and vegetables. The equipment now available is not feasible for routine quality testing; however, costs and capabilities are rapidly improving. Each sensor method is based

on the measurement of a given constituent or property; therefore its ability to measure overall quality is only as good as the relationship of that constituent or property to quality as defined for a particular purpose. Improved statistical methods for combining the inputs from several measurements into classification algorithms are being developed.

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